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RESEARCH ON MILLIMETER WAVE BOLOMETERS

Final Report
12/15/50 to 7/14/52

Baird Associates, Inc.

University Road *Cambridge 38, Massachusetts*

Our J. O. 5069

Office of Naval Research

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RESEARCH ON MILLIMETER WAVE BOLOMETERS

FINAL REPORT
Covering the Period
December 15, 1950
to
July 14, 1952

by

E. Barr
and
L. Mertz

Submitted in accordance
with the terms of the
contract noted above.

Bruce H. Billings
Bruce H. Billings
Director of Research

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ABSTRACT

This report discusses in detail the findings of an investigation focused on the development of bolometers designed to function as practical detectors for radiation between 200 and 1000 microns in wavelength. For the purpose of orderly presentation, the report is divided into several parts as follows.

I. Introduction - Facts and reflections leading to the course of development taken.

II. Development of the sensitive element and supporting substrate.

III. Design of the bolometer housing and mount and the development of suitable means of fabricating and anchoring the sensitive element.

IV. Testing apparatus and methods including results.

V. Conclusion.

Appendix I. Mathematical deduction of the absorption of a material of resistance 189 ohms per square.

Appendix II. Fundamental bolometer theory.

I. INTRODUCTION

For the measurement of low intensity infrared radiation, currently available detection devices rely on the thermal heating produced by that portion of the incident radiation absorbed. There existed a concentration of effort during the 1940's on the development of these devices and from the development there emerged four types of detectors that have reached a high state of perfection and have the test of reliability in commercial usage. These are:

1. High impedance bolometers of which the Bell Laboratory thermistor bolometer is a typical representation.
2. Fast thermocouples such as the Swartz thermocouple.
3. The Golay cell.
4. Low impedance bolometers such as the Baird Associates platinum element bolometer.

In the course of development of these detectors an adequate means of absorbing the incident radiation was constantly pursued. With the exception of the thermistor bolometer* it was necessary to incorporate in the devices a medium to function as a radiation absorber. This procedure imposed an additional problem of electrical stability

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* The thermistor bolometers were found to absorb about 50% of the incident radiation without applying an absorbing layer

and also added mass to the sensitive elements, thereby causing increased time of response.

The methods used by most experimentalists followed directly from the work of Pfund[1] who evaporated metal from a hot wire placed under a Bell jar maintained at reduced atmospheric pressure. The "soot" thus formed was allowed to deposit on a suitably placed element. In pursuing this technique many different metals and parameter variations were tried with each laboratory developing its own artful procedure. However, there emerged from the accumulated maze of empirical information an important fact regarding the choice of metal. The high conductivity metals produce the better blacks, better in that they yield greater absorption per unit mass and greater stability. A comprehensive study of gold blacks was made by Harris, et al[2] during which much of the art of application was removed and the character of the deposits studied with the aid of an electron microscope and infrared spectrometers. His most recent article reports absorption data out to 455μ. At this long wavelength the value of the absorption is of the order of 60%, an encouraging result. (This work was unknown to us before the publication appeared.)

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[1] Pfund, A. H., J. Op. Soc. Am., 24, p. 121 (1934)

[2] Harris, S., and Colby, M. Y., J. Op. Soc. Am., 24, p. 217 (1934)

Several years ago Golay designed his detectors which used in place of an absorbing layer such as described above, a metallic layer whose resistance was approximately 189 ohms/square. For any metal made in such a thickness as to meet this resistance value the absorption will be 50%, the reflection 25%, and the transmission 25%[3]. This result may be obtained mathematically by solving Maxwell's equations[4] or by the impedance matching concepts used in transmission line theory. (The mathematical treatment is included in this report under Appendix I.)

The most important feature of this result is that the absorption is independent of wavelength just as long as the resistance is independent of the frequency corresponding to that wavelength. For most metals this means that the absorption will be uniform and independent of wavelength for those wavelengths longer than about 10μ. To those who have worked with the metal blacks the above method of achieving absorption eliminates much concern, but to utilize this method extremely thin metal layers must be formed. In our view, this could best be done by deposition of the metal layer in high vacuum.

We were satisfied in our minds that the sensitivity expected from bolometers made by using high vacuum techniques would not compare too favorably with the Golay cell. However, the Golay cell, on account of its many parts, occupies considerably more

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[3] W. Waltersdorff, Z. Physik, 91, p. 230 (1934)
[4] Hadley and Dennison, J. Op. Soc. Am., 37 (1947)

space at a crucial point than does a bolometer. Then too, Golay cells are not too satisfactory when subjected to a vibration field such as exists in planes or portable equipment. It might be pointed out that bolometers are not immuned to mechanical vibration either, but they can be made surprisingly rigid.

Though we were convinced that bolometers having a large range of resistances and shapes but characterized by the 189 ohm per square requirement could be made by evaporation, we were aware of the limitations and technical pitfalls as well as the advantages of the method. It might be instructive to list some of the more obvious disadvantages and advantages. Considering first the disadvantages, we have:

1. Thin metal films formed by high vacuum deposition exhibit electrical and optical characteristics considerably different from those of the bulk metal. In general, the resistivity is higher and the coefficient of thermal resistance lower. To be specific and basing judgement on previous experience, metal films 100 or 200 Å thick have resistivities from 3 to 10 times higher than bulk values. The difference depends on the metal under investigation and also on the spud with which the metal is deposited. Those metals classed as poor conductors exhibit the greatest departure from bulk metal constants and have negative thermal resistance coefficients. The absolute value of these negative coefficients increases with decreasing thicknesses. This peculiarity can be used to advantage. Greater departure is also observed for metal films deposited slowly

than for those deposited rapidly. Hass[5] reported that he had succeeded in depositing 200 Å thick nickel that had bulk metal characteristics by affecting the deposition very rapidly.

2. The choice of metals is necessarily restricted by the 189 ohm/square requirement to those classed as poor conductors. Good conductors such as gold or even nickel would have to be made as thin as a few angstroms to meet this requirement. Metal films of this thickness are not stable current conductors and electrical noise would be excessive. Thus, gold and nickel, both metals used with success during the war, must be eliminated.

3. A minor disadvantage but one perhaps worthy of mention concerns bolometer specification. Since the sensitive element thickness is fixed by the 189 ohm/square requirement, it is possible to specify either bolometer resistance or the length to width ratio but not both arbitrarily. The interdependence of the resistance and length to width ratio is

$$L/W = R/189$$

where R is the resistance in ohms and L and W are the bolometer length and width in the same units.

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[5] Verbal Communication from Dr. George Hass of the Army Engineering Laboratory at Fort Belvoir.

Next let us consider the advantages.

1. From the above equation we see that for bolometers of practical size the resistances will be of the order of 200 to 1000 ohms. This range of resistance offers advantages over both the low resistance metal and high resistance thermistor bolometers. Like the low resistance bolometer, electrostatic pickup from these 189 ohm/square bolometers should not be troublesome as is apt to be the case for thermistor bolometers which must use high voltage to push the current through the sensitive element. While the low impedance bolometers demand extreme care in electronic circuitry because of the necessity of maintaining very low noise levels corresponding to the thermal noise level of the bolometer, the requirement here will be less stringent. Noise levels of the order of 10^{-8} volts for a two cycle bandwidth will be tolerable for bolometers of the order of 1000 ohms resistance. Then too, the transformers necessary to introduce the signal into the first stage of the amplifier need not be so massive because the required turns ratio to raise the impedance of the bolometer to that of the first tube is inversely proportional to the bolometer resistance. It would appear that from these observations that the 189 ohm/square bolometers might be used with commercially available amplification equipment.

2. The possibility of making unsupported sensitive elements from germanium or tellurium is worthy of exploration. The evaporation

process is ideal for this purpose and perhaps elements made from one of these materials will be thick enough to exhibit bulk metal characteristics. In passing it might be well to point out that all practical shapes and sizes can be achieved by affecting the deposition through appropriate masks.

3. These bolometers, once produced, could be installed in portable equipment and subjected to rather severe vibration without suffering physical damage. It is believed that these units could be made as free of vibration difficulties and the conventional low impedance metal units with the advantage of being useful for any wavelength above 10μ.

The next section discusses the development of the sensitive element starting with the experimental attempts to produce unbacked elements of germanium and tellurium and ending with the development of a suitable substrate for bismuth elements.

II. DEVELOPMENT OF THE SENSITIVE ELEMENT AND THE SUPPORTING SUBSTRATE.

In manufacturing bolometers with particular impedance characteristics, a choice of resistance material had to be made that would satisfy certain stability requirements without sacrificing performance. The impedance desired here, 189 ohms/square, suggested two approaches in element manufacture. One approach was that of self supporting elements made from one of the metals exhibiting high resistivity such as tellurium or germanium; the other was that of using a metal of low resistivity deposited on a thin supporting film. The first of these methods was considered the more inviting since it would permit the direct manufacture of elements without pursuing the art of making and contending with the questionable stability of thin organic supporting films.

Previous experience in making unsupported metal films by vacuum distillation served notice that any film thus formed and having tolerable mechanical stability would have to be at least 1000 Å thick. Two conditions were thus imposed; one, that the impedance of the element be 189 ohms/square and the other that the element thickness be 1000 Å. These conditions limited the choice of metals to two: germanium and tellurium. Relatively thin layers of tellurium proved chemically unstable after removal from the vacuum chamber in which they were made. Most probably

oxidation caused the resistance rise that continued for several days. Usually after one day the resistance values were so large that it could not be evaluated by using conventional laboratory ohmmeters. The suggestion was made that a film of Te of proper thickness could be deposited and subsequent protective oxide allowed to form so that the final resistance would be approximately 189 ohms/square. The suggestion was never carried out fearing that inability to reproduce results would blunt the attempt. Instead, considerable effort was placed on the deposition of germanium, and here the problem was not one of chemical stability but rather one involving a satisfactory means of evaporation. Tungsten helices made from 0.040" diameter wire were first used as evaporation sources. Small chunks of Ge were placed inside of the helix. The Ge could be melted without difficulty but the apparent high conductivity of molten Ge shorted the helix so that only very thin layers could be deposited without burning out the filament. Tantalum and molybdenum boats were tried and proved somewhat more successful. However, the Ge attacked these materials and thus caused filament failure as before. Next, two 0.060" diameter tungsten wires 4" in length were attached to rigid filament supports with a spacing between the wires of approximately 1/16 near the center and increasing to 1/2" at the support posts. Small chunks of Ge were placed in the channel formed by the wires. By applying sufficient power to this parallel wire filament the Ge was melted and flowed along the channel toward the cooler ends

of the filament. The flow ceased at a point where the surface tensional forces could no longer sustain the weight of the metal. The length of filament covered by the molten metal was about 1". Using this type of filament with rigid supports caused the filament to bend out of shape and repeated use of the same filament was not possible without reshaping the wires. A more reliable source was then made using thick Ta from which boats were fashioned. This Ta stork was 0.010". Boats made from this stork were used for as many as ten separate evaporations before they were burned out.

In the course of developing improved means of evaporating Ge, films of the latter were deposited on suitable surfaces. For the most part sodium fluoride was first deposited by evaporation onto a clean glass blank. The optical thickness of this layer was approximately 1/2 wave for the middle of the visible spectrum. Following the Ge deposition the blank was slowly lowered into water with the Ge side up. Care was taken to lower the blank until the surface was slightly below the water level. Surface tension prevented the water from running over the metal. Then, a small amount of the Ge film was scratched away with forceps to permit the water to touch the fluoride. Upon dissolving, the fluoride lowered the surface tension of the water, thus inviting the latter to creep under and lift the Ge film. In spite of these relatively weak forces the Ge films invariable split apart so that no predetermined size could be obtained even on the surface of the water. For films much thicker than those having resistances of

189 ohms per square the splitting action still persisted. Consequently, further extension of this work did not appear wise. Instead, attention was given to the fabrication of supported bolometer elements.

In any development involving thin supports for bolometer elements, prime consideration must be given to the heat capacity of the support. This involves techniques to enable one to make very thin and also very tough films. Organic films are currently used in most laboratories as delicate supports; of the various organic materials possible nitrocellulose is one of the best as to toughness, stability and reproducibility. Nitrocellulose was used throughout our work. It must be stated in advance of description that organic film making is still an art and fool proof procedures cannot as yet be stated. The method used in this laboratory is discussed immediately below.

The nitrocellulose solution found most satisfactory was made using

20 hr. Wet, 500 sec. Nitrocellulose

300 cc. Ethyl Acetate

75 cc. Amyl Acetate

75 cc. Acetone

This solution was mixed well and filtered through glass wool and then allowed to age for several days before using. Films made

with aged solution are tougher than those made using fresh solution. In using the "wet" 600 sec. nitrocellulose the variable "wet" is apparently indeterminate. We first used solution made from this formula but which we had on hand from previous work. Later attempts to reproduce this solution met with varying degrees of success and a plausible explanation is that the wetness of the various samples of nitrocellulose was not the same in the several cases. We did not pursue the problem but worked with the best we could produce.

In preparing to make films a large basin was filled with tap water that had been running for sometime, thus cleaning the pipe of some foreign material and getting water at its lowest temperature without the addition of a means of cooling. A small amount of solution was then drawn into a medicine dropper and just prior to dropping the solution on the water the surface of the latter was cleaned by gently dragging a paper towel over the surface. The solution was then dropped and allowed to spread. The basin was large enough to permit the solution to spread out without obstruction. The film thus formed was picked up by inserting a 4" square metal frame under the water and raising the plane of this frame vertically. The raised film thus covered each side of the frame forming a double film. The color by reflected light of these double films was usually pale yellow indicating a quarter wave optical thickness. Assuming that the wavelength of this color to be, in round figures, 6000 Å and the index of reflection to be 1.5, the actual thickness of these films were 1000 Å. The

variation in color across the 4" frame indicated only a few hundred angstroms variation in thickness. Usually a section an inch or so in diameter could be found exhibiting the proper color and uniformity for mounting purposes. The day to day difficulty in making these films was not so much a matter of achieving a given thickness but rather one of getting films with the same degree of toughness and with no pinholes. Undoubtedly the control of humidity, P.H. and temperature of the water would make the process more scientific. These controls were not initiated for lack of time.

The next section discusses the design of the bolometer mount and the fabrication of the sensitive element.

III. DESIGN OF THE BOLOMETER HOUSING AND THE DEVELOPMENT OF SUITABLE MEANS OF FABRICATING AND ANCHORING THE SENSITIVE ELEMENT

In the development of any bolometer a great deal of time is taken up in devising an appropriate bolometer housing. We decided, therefore, to adopt the Bell Laboratory Thermistor housing currently manufactured here at the Baird laboratory. The base part of this mount made of 0.010" thick kovar formed in an appropriate press to the shape of an inverted pie tin. Five holes are punched in the disc to introduce four electrical leads and an evacuation tube. The four lead holes form the corners of a square, and the hole for the pumping tube is located at the geometrical center of the square. The leads are made from 0.040" diameter Kovar wire. These leads are anchored and insulated from the base by dropping a small glass bead over the wire and fusing the glass to both the lead and base. The seals are also vacuum tight. The cap for these bases is made of silver formed into the shape of a cup. The open end of the cup fits onto the base and may be soldered in place. A hole of such size as to allow a small shoulder for the window is punched in the other end. Ordinarily silver chloride is used for the window material. This window is sealed in place by laying the silver chloride on the

shoulder and fusing the portion of the chloride to the silver by inserting the sleeve into the coil of an induction heater. For long wave work crystalline quartz was used in place of the silver chloride. In this case the seal was made with apiezons 'W' wax.

The problem of mounting the substrate and sensitive element was solved in several ways. These are discussed in the order of their trial.

The first method involved the use of a glass disc 3/8 of an inch in diameter and 1/16" thick. This size disc fitted snugly on the inside of the base pins. A slot was cut in the disc by sandblasting through a rubber mask. To affect the sandblasting a homemade nozzle was fashioned by building a simple aspirator into the available air line. A metal tip was placed at the end of the air line with a free opening of 1/8". A small metal tube was fitted through a hole in the side of this tip and soldered in place. This tube was tilted slightly in the direction of the escaping air stream. By applying air pressure, carborundum was sucked into the tip and projected against the glass. Two hundred mesh carborundum was found sufficiently fine in grain size to render the edges defined by the rubber mask free of chips. The slot through the 1/16" thick glass could be made in about five minutes. These slots were made about 2.5 mm in length by about 1.5 mm in width.

Following the sandblasting, Hanovia silver paste was painted onto the disc rim in segments separated by a clear space. Small silver wires 0.010" in diameter were embedded in the paste and the whole thing baked at about 400° C. The baking was continued until the glass under the paste turned slightly yellow. These wires were thus firmly attached to the glass and subsequently served to attach the disc to the lead wires in the housing base and also to make contact with sensitive element.

Before attaching the disc to the base the nitrocellulose substrate, discussed in Section II, was taken out of the water from which it was formed and placed on the disc. The frame used to remove the nitrocellulose from the water was held free of motion until after the portion in contact with the glass was completely dry. The excess film was then removed with tweezers. Upon drying the film drew taut over the slot and adhered tightly to the surrounding glass.

The next operation involved the deposition of the sensitive element. This was done by high vacuum evaporation. We chose bismuth metal. This choice was based on previous experience[6] on the recent work of Czerny, et al[7] and on the fact that the resistivity of bismuth is such that the necessary thickness to meet the 189 ohm/square requirement is great enough to ensure electrical stability but not so thick as to add greatly to the

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[6] Government Contract OSRD NO. 6597, (1946)

[7] Czerny, M, Kofink, W., and Lippert, W., Ann. der Physik, 6, p. 65 (1950)

specific heat inherent in the nitrocellulose substrate.

The filament from which the evaporation was affected was made of tantalum strip stock. A strip $\frac{1}{8}$" wide and 3" long was dented in the center by pressing a ball bearing against the tantalum backed with a soft wood block. The dent thus formed served to prevent the bismuth, upon melting, from rolling off the tantalum. The ends of this strip were then anchored to terminal posts projecting above the base of the vacuum chamber. Immediately above the filament a horizontal baffle plate was attached to a vertical rod passing through the base plate. In practice the baffle was placed over the filament prior to deposition. When the gas pressure in the chamber was of the order of 10^{-4} mm of Hg or better the temperature of the filament was raised until the bismuth melted and began evaporating. It was believed that in this operation much existing foreign matter in or on the surface of the bismuth was driven off but prevented from reaching the target mounted vertically above. Following this precaution the baffle was moved to one side of the filament and the bismuth allowed to condense on the target and a resistance measuring device. At the moment the resistance reached a value corresponding to 189 ohms/square the baffle was moved back over the filament thus terminating the deposition.

The target, in this case the bolometer mount with its accompanying substrate, was placed vertically above and at a

distance of one foot from the filament. At this distance, thickness uniformity could be expected over the small areas in question. The mount was laid on a piece of thin brass strap which had previously been machine slotted. The long direction of the rectangular hole in the mount was made parallel to the slot and properly centered with respect to the line parallel to and passing through the center of the slot. The slotted mask served only to define the width of the sensitive element. The resistance measuring device was mounted adjacent to the bolometer and in the same horizontal plane. This device consisted of a 1" square piece of glass with silver contacts on two opposite edges. The silver was deposited by evaporation and by using a mask the contacts were separated by $\frac{1}{4}$". This glass was then slipped into a small fixture fitted with spring slips to hold the glass and the electrical leads attached to insulated terminals in the baseplate of the evaporator. A Simpson meter was used to follow the resistance during the course of the deposition. From the geometry of the space between the contacts the desired resistance was 189/4 or about 47 ohms. Once the deposition was terminated by swinging the baffle over the filament, no further change in resistance was detected. Upon emitting air to the chamber a small increase in resistance was noted corresponding to only a few ohms per square.

Now the slot in the mask used to limit the width of the sensitive elements was an inch or so in length. Upon removing the

glass mount from the vacuum chamber the bismuth ribbon extended over the whole mount. To make the bolometer length of the sensitive element definite and uniform across the width of the element it was necessary to deposit contacts at the ends. This was accomplished by laying a strip across the bolometer equal in width to the desired element length and evaporating silver on the remainder of the mount. This silver further served as a means of attaching the leads from the housing base to the sensitive element. Care was taken in the deposition of the silver to make it thick enough to ensure against resistive heating when subjected to the bolometer voltage. When the contacts are made insufficiently thick excessive electrical noise is ensured.

Following the deposition of the contacts the mount was positioned between the electrical lead pins of the housing base and anchored by means of the small silver wires previously attached to the rim of the glass disc with Hanovia silver paste. In making the solder joints a small amount of solder was flowed onto a part of each silver bolometer contact. In this way good electrical contact was made between the housing pins and the sensitive element. The next step was that of testing the bolometer characteristics. These tests are discussed in the following section (IV). Before proceeding to this section, however, it might be well to discuss several modifications in element mount design.

Essentially these modifications involved means of eliminating the need for the sandblasted slot in the mount disc. In the first of these modifications 0.010" diameter silver wires were placed on a solid glass disc and separated by a distance equal to the desired element length. These wires were anchored to glass silver paste. The nitrocellulose substrate was laid down as before and upon drying drew taut over the wires leaving a 0.010" space between the glass and spacing. Although this modification eliminated the need for sandblasting a slot in the glass, the small silver wires presented a dangerously small area for the subsequent evaporated contacts. A further modification was made by eliminating the glass altogether. Instead, two 0.040" diameter wires were fashioned in the form of an arch with a flat top. The four ends were then soldered to the housing pins, one to each pin so that the two arches were parallel and separated by a spacing equal to the desired element length. The top of these wires were then filed down until the width of the flattened wires was equal to the diameter of the original wire. Thus, a contact width of 0.040" was realized. Although these modifications were used, sufficient tests were not made to afford adequate appraisal. The latter modification was, however, considered promising in regard to simplicity.

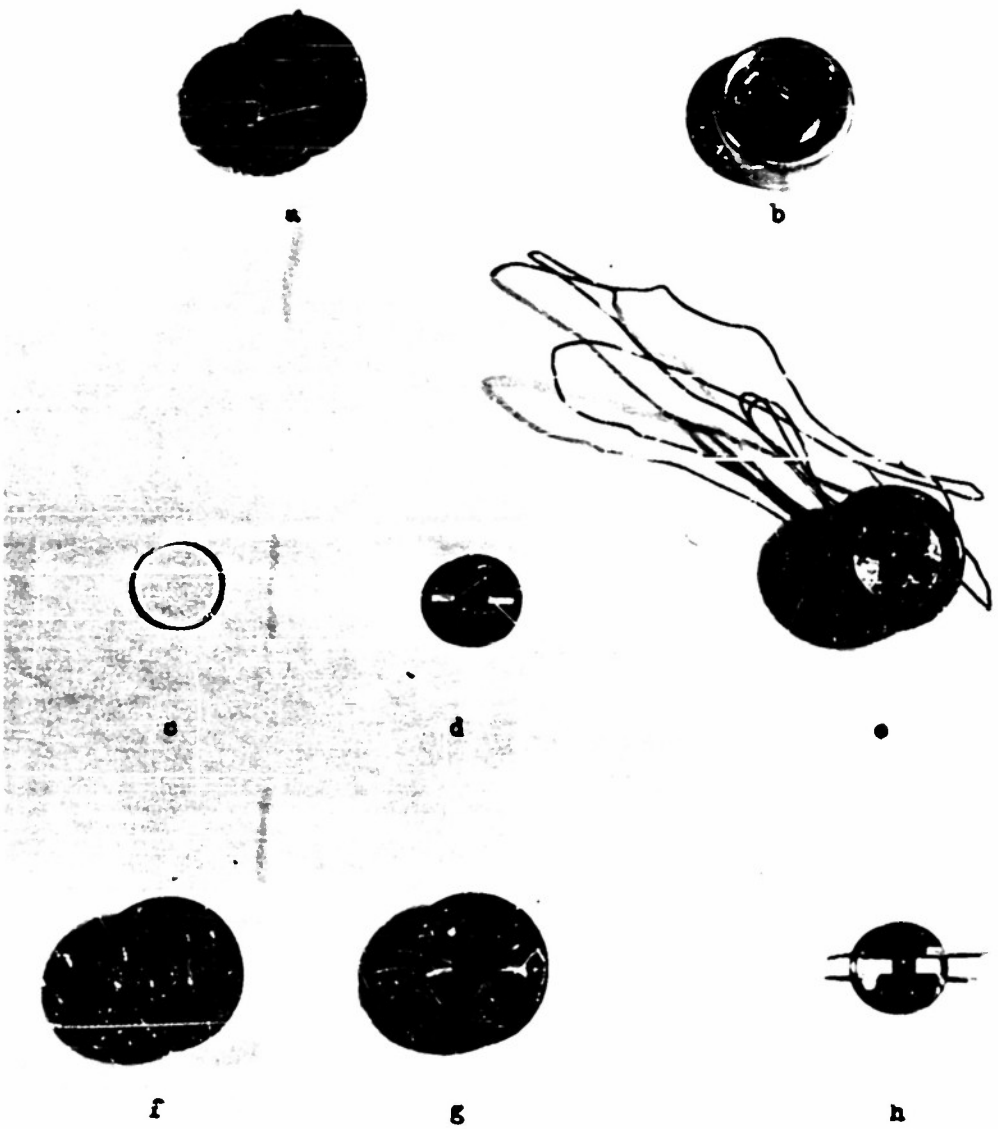

FIG. 1

a, b ..... base and cap.
c, d, e ..... glass disc, element over sandblasted slot, completed bolometer
f, g ..... flattened wire mount, element over flattened wires.
h ..... element mounted over round wires in contact with the glass.

IV. TESTING APPARATUS AND METHODS INCLUDING RESULTS

The first measurement made following the manufacture of a bolometer was that commonly known as a cold resistance of the bolometer. This is the resistance of the bolometer at ambient temperature. A Wheatstone bridge and galvanometer setup was used for this determination. A high resistance was placed in series with the battery so that a small current of a milliampere passed through the bolometer. The resistive heating of the sensitive element caused by this small current was negligible.

This same apparatus was used in determining the resistance as a function of the temperature of the element. From these data the coefficient of thermal resistance of the element was determined. The actual bolometer was employed for this purpose as opposed to the indirect method of depositing a similar layer of bismuth on a solid backing such as glass. The bolometer was inserted in a test tube closed with a rubber stopper. Copper leads from the bolometer were brought out along the test tube and held in place by the stopper. Then the whole test tube was placed in an oil bath and the oil heated very slowly with a bunsen flame. The oil was constantly stirred during the heating and a thermometer placed adjacent to the test tube. The time required to raise the temperature of the oil from that of the room to 110° C. was about

three quarters of an hour. Resistance readings were made at ten degree intervals for 30° and 100° C. A typical curve as a resistance of function of temperature is shown in Fig. 2. We know, first of all, that this curve is not a straight line, showing, of course, that the coefficient of thermal resistance itself is a function of the temperature. Secondly, the resistance is a decreasing function of the temperature. In lieu of previous work done in making bolometers by evaporation, this negative value for the thermal coefficient is not surprising. Although the coefficient for bulk bismuth is positive in thin layers made by vacuum deposition, an increase in temperature apparently has the effect of crowding the pseudo crystals closer together - thus giving an effective lower resistance. It is believed that if it were possible to measure resistance as a function of temperature for any one of these small crystalline glomerates it would be found to be an increasing function. The value of the coefficient of bismuth for various temperatures is also shown in Fig. 2.

As stated in a previous section of the text it seemed probable that the numerical value of this coefficient could be altered depending upon the method of deposition. By affecting the deposition very rapidly, less tendency to crystallize would seem probable. An attempt was made to alter the coefficient by varying the rate of deposition for different bolometers. We were not successful in changing the coefficient by any significant

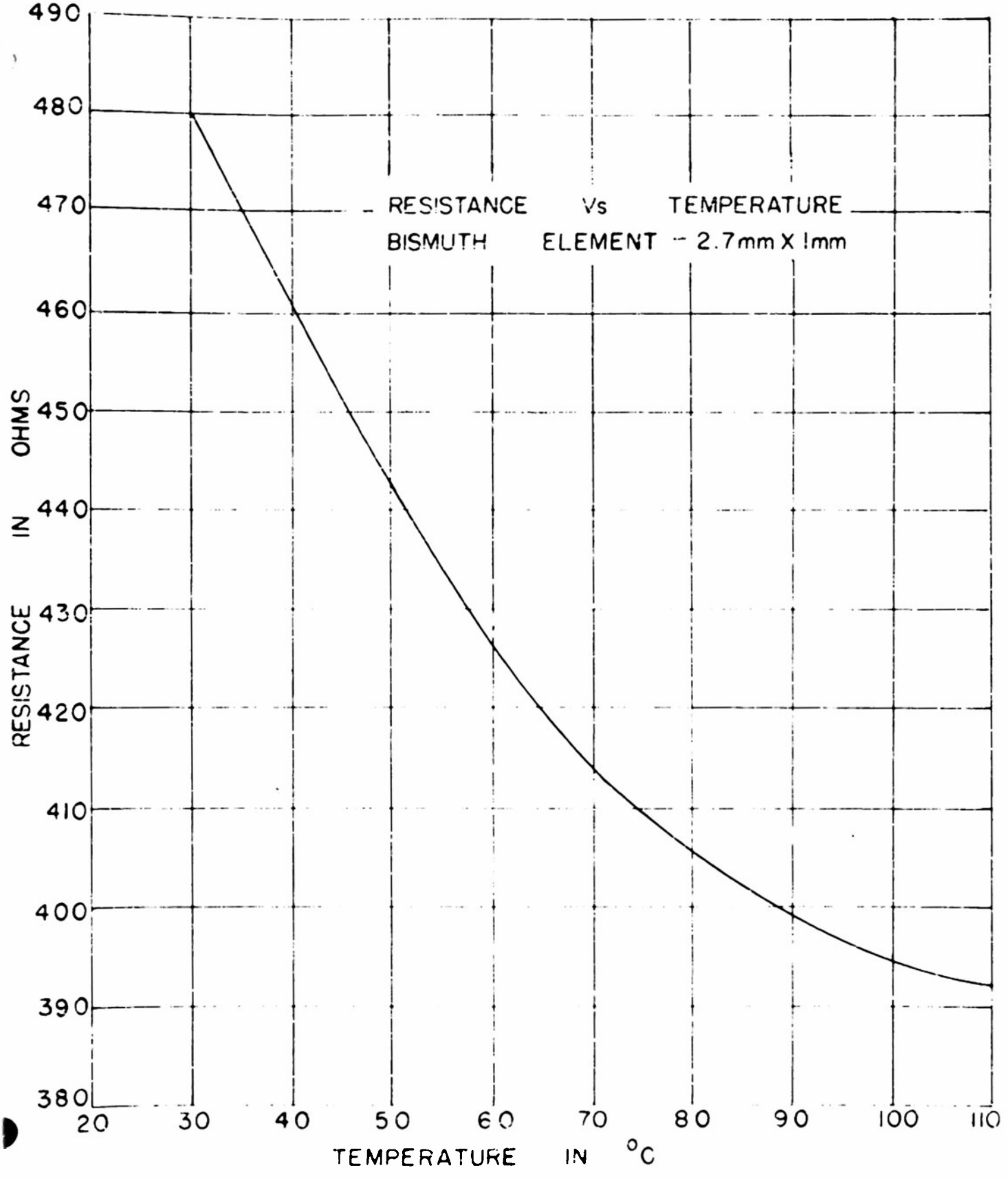
RESISTANCE Vs TEMPERATURE
BISMUTH ELEMENT - 2.7mm X 1mm
RESISTANCE IN OHMS
490
480
470
460
450
440
430
420
410
400
390
380
20
30
40
50
60
70
80
90
100
110
TEMPERATURE IN °C

FIG. II

amount. The small changes noted were such that those bolometers made by evaporating the metal very rapidly exhibited a coefficient less negative than those made by fast evaporation, but this negative characteristic only served to give a smaller numerical coefficient making the response of the bolometer smaller. The next measurement made on the bolometer was that of the response. Here the response is defined as the RMS voltage output per peak to peak watt input. The noise of the bolometer does not enter into this measurement unless it is excessively large, approaching in magnitude that of the bolometer output itself.

A black body radiation source was constructed as follows. A brass tube 10" long and 2" in diameter was fitted with end plates. Through the center of one of these end plates a $\frac{1}{2}$" diameter hole was drilled through which the radiation was emitted. Into the wall of the tube a small hole was drilled and a metal tube soldered into this hole to accommodate a thermometer. Thin asbestos tape was then wound around the large tube and wetted to make it stick firmly. Nichrome ribbon was it turn wound around the asbestos covered tube with a wire to wire spacing of about $\frac{1}{4}$". Another application of asbestos was then made and wetted as before. The whole tube was then inserted in an oven and dried out. This tube was then mounted on a metal base plate directly behind a $\frac{1}{4}$" diameter iris. The distance between the iris and the hole in the cylinder was made about 3/4". A square wave chopper and motor combination was

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mounted on this same base plate so as to chop the radiation between the iris plate and the emitting hole of the source. The radiation from the source was chopped at 10 cycles per second.

The bolometer in turn was placed directly in front of and at a distance D from the iris. The value of D could be chosen at will so long as the bolometer element itself saw only the radiation streaming from the $\frac{1}{4}$" hole in the source. A simple calculation showed that any value of D greater than 2.2 centimeters could be allowed. The equation* employed to calculate the energy incident on the bolometer was

$$U = \frac{AR_1^2}{R_1^2 + D^2} \qquad (1)$$

Where ρ is the black body radiation constant times the difference in the fourth power of temperature of the inside of the source and room temperature. A is the area of the bolometer in square centimeters, R is the radius of the iris in centimeters, and D is the distance between the iris and sensitive element.

The bolometer was coupled to the transformer of the amplifier by use of a square arm bridge. Since it was a nuisance to change the value of the bridge resistances to match values of bolometer resistances, we chose the shape of the bolometer such that their resistances were of the order of 600 ohms, thus enabling us

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* Richtmyer and Kennard, "Introduction to Modern Physics", McGraw-Hill Book Company (1947)

to use a fixed bridge made using 500 ohm wire wound resistances. This bridge assembly was made as compact as convenient and placed on the inside of a metal tube to minimize the possibility of pickup. The bridge current was supplied from a storage battery in series with a variable resistance box. The current through the bolometer was determined by measuring the voltage across a 10 ohm wire wound resistor placed in series with the bolometer. The voltage drop across the bolometer was measured using the same meter. From these values of current and voltage the resistance was determined. The bridge was coupled to a transformer whose primary impedance was of the order of 500 ohms. The output from the transformer was connected to the grid of the first tube of the 10 cycle narrow band amplifier. The peak response of this amplifier was centered at 10 cycles with a bandwidth of 2 cycles. The adjustable gain control permitted a gain variation between 1 and 50 times 10^6. The noise of the bolometers was measured for each current value with the bolometer capsule covered with a black card. Two important observations were made. One, if the current was increased, a point was always reached at which further increase of current failed to produce an increase in the response. This was due to the fact that the numerical value of the coefficient of thermal resistance is smaller for high temperatures. Secondly, the bolometer invariably became noisy at the point of greatest response. The temperature corresponding to the point of maximum

response did not, however, approach the temperature at which the bolometer burned out. In fact the current through the bolometer could be doubled without damage. The best signal to noise ratio was obtained by employing currents of the order of 5 mils through these 500 ohm bolometers. The response and noise measurements are given in Table I together with the rough value of the time constant.

The time constant was measured by assuming exponential response and measuring the shape of the curve. The bolometer was coupled directly to a wide band amplifier and was irradiated by pulses of visible light about 33 milliseconds apart. When the output signal was put on the scope with the horizontal adjusted to 33 square units between pulses, each horizontal square unit represents one millisecond. The vertical gain was then adjusted so that the peaks of the pulses were 27 square units high. The time lag to drop from 27 to 10 units (that is, 1/e) was read directly in milliseconds. The proper accuracy in this method was of the order of $\frac{1}{8}$ millisecond. The time constants were between 3 and 4 milliseconds with the bolometer element in air and about 20 milliseconds in vacuum.

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TABLE I

RESPONSE AND NOISE OF THREE BISMUTH BOLOMETERS

Bolometer No.	Operating Current (ma)	Element Resistance (ohms)	Response Rms Volts Peak to Peak Watts	Noise Rms Volts 2 Band-width
1	6.7	450	0.60	3×10^{-8}
2	8.0	380	0.55	4
3	6.5	520	0.62	3

The dimensions of the above bolometers were 2.7 mm in length by 1 mm. in width.

The operating temperature was 30° C. above room temperature. Any temperature rise made by increasing the current increased the noise without an accompanying increase in response.

The minimum detectable signal (signal to noise) was about 10^{-8} watts.

V. CONCLUSION

We can conclude from the results of our work that bolometers can be made possessing the 189 ohm per square characteristic and having sensitivities within a factor of ten of the very best detectors used for short wave radiation. These bolometers of intermediate impedance can be made in a variety of shapes and sizes by the evaporation process and possess merit on this account. We believe that with effort means could be found whereby the coefficient of thermal resistance could be improved by improving the technique used in depositing the sensitive element. Also, the nitrocellulose backing film might be eliminated and an improved backing made of quartz or aluminum oxide substituted in its place. Hass's method of making aluminum oxide films and Strong's nickel carbonyl process lend themselves readily to this thin pellicle development.

APPENDIX I

Let us consider a plane metal sheet of thickness d and of infinite extent in the y-z plane, as shown in Fig. 1. Regions 1 and 3 in the figure are infinite dielectric media characterized by the propagation constants $k_1 = \frac{2\pi n_1}{\lambda}$ and $k_3 = \frac{2\pi n_3}{\lambda}$, where n_1 and n_2 are the ordinary indices of refraction. Region 2 is characterized by the propagation constant $k_2 = 2\pi (\eta + i\chi)/\lambda$. When the wavelength is sufficiently long η and k are large in comparison to with unity and both approach the value $\sqrt{\sigma/2\omega\epsilon_0}$.

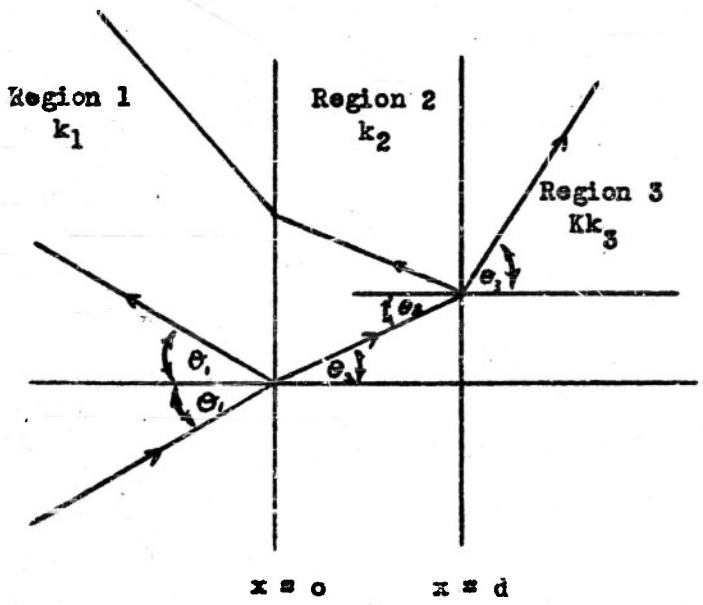

FIGURE 1

This may be shown as follows. From electromagnetic theory it is known that the general relationship between the constants η and ϵ, μ and σ is obtained from the propagation constant k.

$$k^2 = \omega^2 \epsilon \mu + i\omega\mu\sigma \tag{1}$$

For this expression ϵ is the permittivity, μ the permeability, and σ the conductivity of the metal, and ω is the angular frequency = $2\pi f$. The propagation constant for free space is

$$k_o^2 = \omega^2 \epsilon_o \mu_o \tag{2}$$

The ratio of k to k_o is

$$\frac{k^2}{k_o^2} = (\eta - i\kappa)^2 = \frac{\epsilon\mu}{\epsilon_o\mu_o} + i\,\frac{\mu\sigma}{\omega\epsilon_o\mu_o} \tag{3}$$

For non-magnetic materials $\mu = \mu_o$ and

$$\eta - i\kappa = \left[\frac{\epsilon}{\epsilon_o} + i\,\frac{\sigma}{\omega\epsilon_o}\right]^{\frac{1}{2}} \tag{4}$$

Squaring

$$\eta^2 - \kappa^2 - 2i\eta\kappa = \frac{\epsilon}{\epsilon_o} + i\,\frac{\sigma}{\omega\epsilon_o}$$

Equating real and imaginary parts

$$\begin{cases} \eta^2 - \kappa^2 = \dfrac{\epsilon}{\epsilon_o} \\ 2\eta\kappa = \dfrac{\sigma}{\omega\epsilon_o} \end{cases}$$

The solution of these simultaneous equations yields

$$\eta^2 = \frac{\left(1+\frac{\sigma^2}{\omega^2\epsilon^2}\right)^{\frac{1}{2}}+1}{2\frac{\epsilon_0}{\epsilon}} \qquad (5)$$

$$K^2 = \frac{\left(1+\frac{\sigma^2}{\omega^2\epsilon^2}\right)^{\frac{1}{2}}-1}{2\epsilon_0/\epsilon}$$

For wavelength of the order of microns and for metallic materials $\frac{\sigma^2}{\omega^2\epsilon^2}$ is much larger than unity and Eqs. (5) reduce to

$$\eta = K = \sqrt{\frac{\sigma}{2\omega\epsilon_0}}$$

To obtain the reflection and transmission coefficients of the metallic layer it is necessary to solve Maxwell's equations with the appropriate boundary conditions. This is a straightforward, although laborious, task and only the results will be given here.

Details of the deviations may be found in a paper by Hadley and Dennison[1]. The equations assume that the wavelength is long and that the layer is very thin. For the ray polarized

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[1] Hadley, L. N., Dennison, D. M., Reflection and Transmission Filters, Part I, J. Op. Soc. Am., 37 (1947).

normal to the plane of incidence we have

$$R_{\perp} = \frac{\left[\frac{1}{p} - \frac{1}{g} + \frac{f}{pg}\right]^2}{\left[\frac{1}{p} + \frac{1}{g} + \frac{f}{pg}\right]^2}$$

$$T_{\perp} = \frac{\frac{4}{pg}}{\frac{1}{p} + \frac{1}{g} + \frac{f}{pg}} \qquad (6)$$

$$A_{\perp} = \frac{\frac{4f}{pg^2}}{\frac{1}{p} + \frac{1}{g} + \frac{f}{pg}}$$

For the other polarization

$$R_{\parallel} = \frac{\left[\frac{n_1^2}{p} - \frac{n_3^2}{g} - f\right]^2}{\left[\frac{n_1^2}{p} + \frac{n_3^2}{g} + f\right]^2}$$

$$T_{\parallel} = \frac{\frac{4n_1^2 n_3^2}{pg}}{\left[\frac{n_1^2}{p} + \frac{n_3^2}{g} + f\right]^2} \qquad (7)$$

$$A_{\parallel} = \frac{4fn_1^2/p}{\left[\frac{n_1^2}{p} + \frac{n_3^2}{g} + f\right]^2}$$

where

$$f = \sigma d \sqrt{\frac{\mu_o}{\epsilon_o}} = 120\pi \sigma d$$

$$p = (n_1^2 - \sin^2\theta)^{\frac{1}{2}}$$

$$s = (n_3^2 - \sin^2\theta)^{\frac{1}{2}}$$

when $f = 1$, $\frac{1}{\sigma d} = \sqrt{\frac{\mu_o}{\epsilon_o}} = 120\pi$ ohms, the impedance of free space. The significance of $\frac{1}{\sigma d}$ is easily obtained. The resistance of a slab of material L units long and having a cross sectional area A is

$$r = \frac{\rho L}{A} \qquad (\rho = \text{resistivity} = \frac{1}{\sigma}) \tag{8}$$

If the shape of the conductor is a square of side L and thickness d

$$r = \frac{L}{\sigma L d} = \frac{1}{\sigma d} \tag{9}$$

$\frac{1}{\sigma d}$ is then the resistance of a metallic layer in units of ohms per square. When $f = 1$, the resistance of the layer in ohms per square matches the impedance of free space and f, in general, is a measure of the resistance of the film.

The maximum value of the absorption coefficient for each polarization may be found by differentiating the last of Eqs. (6) and

(7) and setting the derivative equal to zero. For the perpendicular component we have

$$f_{max} = p + g$$

For the parallel component

$$f_{max} = \frac{n_1^2}{p} + \frac{n_3^2}{g}$$

and the absorption in each case is

$$A_{max_\perp} = \frac{p}{p+g}$$

$$A_{max_\parallel} = \frac{gn_1^2}{gn_1^2 + pn_3^2} \qquad (10)$$

$$= \frac{1}{1 + \frac{p}{g}\frac{n_3^2}{n_1^2}}$$

At normal incidence and when $n_1 = n_3$ these expressions reduce to

$$A_{max} = \tfrac{1}{2}$$

Under the same conditions

$$R = T = \tfrac{1}{4}$$

The value of f corresponding to this situation is 2. This means that

$$r = \frac{1}{\sigma d} = \frac{1}{2}(120\pi) = 60\ \Omega/\square$$

$$= 189\ \Omega/\square$$

A metallic film having a resistance of 189 ohms/square imbedded in a dielectric medium and normal to the incident radiation will, therefore, reflect 25% of the energy, transmit 25% of the energy and absorb 50% of the energy in the incident wave.

APPENDIX II[1]

BOLOMETER THEORY

The static conditions of a bolometer are described by the equations

$$\beta\theta - I^2F - Y = 0 \qquad (1)$$

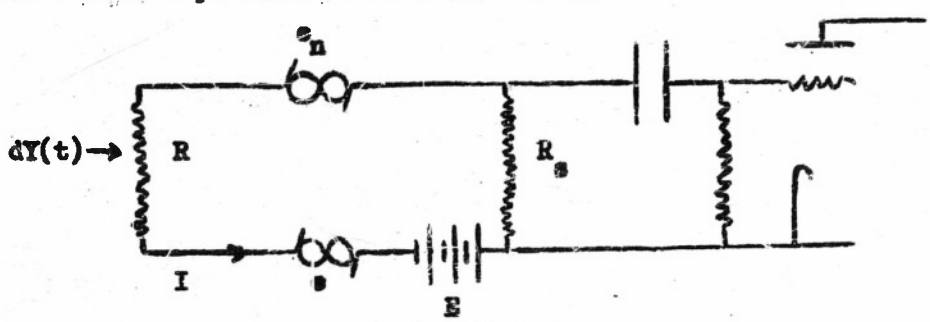
β is called the cooling constant of the bolometer and incorporates the heat loss of the bolometer strip by radiation, conduction, and convection. θ is the temperature of the bolometer, I^2F is the ohmic heating of the bolometer and Y is the radiation incident on the bolometer from all of its surroundings. Differentiation gives

$$\beta d\theta - I^2dR - 2IdI - dY = 0 \qquad (2)$$

These differentials are not all independent. By definition the temperature coefficient of resistance α gives us

$$dR = R\alpha\, d\theta \qquad (3)$$

The electrical terms can best be ascertained by the consideration of an equivalent electrical circuit



[1] Billings, B. H., Hyde, W. L., Barr, E., J. Op. Soc. Am., 37 123 (1947)

R represents the bolometer, R_g the load resistance, and E is a constant battery voltage. E is proportional to the voltage across the Wheatstone bridge in actual practice, e represents effective voltage variations which result from bolometer resistance changes dR. dY(t) is the radiation input to the bolometer - a function of time. e_n is the effective noise voltage. This will primarily be thermal agitation noise. It consists of an alternating voltage of approximately constant amplitude with Fourier components of approximately equal energy per unit frequency interval. It cannot be assigned any specific frequency.

From this circuit an application of ohms law yields

$$dI = -\frac{E}{(R+R_g)^2}\,dR \tag{4}$$

and

$$e = \frac{E\Delta R}{R+R_g} \tag{5}$$

If the variations are considered with respect to time the differential equation (2) must also include a term for the energy which goes into heating the bolometer.

$$h\,d\left(\frac{d\theta}{dt}\right) + \beta\,d\theta - I^2dR - 2IRdI - dY = 0 \tag{6}$$

h is now the thermal mass, or heat capacity, of the bolometer.

Combining Eqs. (3), (4), (5), and (6) simplifies this equation to

$$h\left(\frac{d}{dt}\right) + \beta e - \frac{EIR\alpha}{R+R_g}\left(1 - \frac{2R}{R+R_g}\right) e - \frac{ER\alpha}{R+R_g} \Delta Y = 0 \qquad (7)$$

$\left(\frac{R}{R+R_g}\right)$ and $\left(1 - \frac{2R}{R+R_g}\right)$ both have absolute values less than one. Also, α is so small that $EI\alpha$ is about one hundred times less than β so that the third term of the differential equation is much less than the second. Neglecting the third term for this reason and replacing $\frac{R}{R+R_g}$ by the letter C gives

$$h\left(\frac{de}{dt}\right) + \beta e - EC\alpha\Delta Y = 0 \qquad (8)$$

If the chopping is to be sinusoidal then ΔY will have the value $Y \cos \omega t$ as a function of time. Thus,

$$h\frac{de}{dt} + \beta e - EC\alpha Y \cos \omega t = 0 \qquad (9)$$

This is the equation of a forced oscillation and has the solution

$$e/Y = \frac{EC\alpha}{(h^2\omega^2 + \beta^2)^{\frac{1}{2}}} \qquad (10)$$

The units of this equation, the AC response, would be volts per watt. However, since the voltage can be amplified electronically the equation does not express the performance to be expected from the bolometer.

The performance of any measuring apparatus is usually best expressed as a signal to noise ratio. Dividing the AC response by the noise gives the AC sensitivity which is a more significant value.

The noise will be primarily from thermal agitation. It is possible to reduce the amplifier noise to a sufficiently low level so that it can be neglected in comparison to the bolometer noise. The noise from thermal agitation results from the voltage generated across the bolometer by the electrons as they pursue their thermal motions. The value of this is found to be

$$\overline{e} = \sqrt{4k\Theta_A R \Delta f} \tag{11}$$

where k is Boltzmans constant and Δf is the bandwidth observed around the chopping frequency. Θ_A is the absolute temperature of the bolometer strip. This is not the same as Θ. Θ expresses the temperature of the bolometer above that of the surroundings for the application of Newton's law of heat flow. Θ_A is much larger than Θ and differs from it by a constant. For practical calculation Θ_A can be considered constant and equal to room temperature.

This bandwidth Δf cannot be made indefinitely small and at best it is given by $\Delta f = \frac{1}{2}\pi t$, where t is the time required for each measurement.

$$\frac{1}{\Upsilon}\frac{e}{e_n} = \alpha E \propto \left[(h^2\omega^2 + \beta^2)(4KGR\,\Delta f)\right]^{-\frac{1}{2}} \tag{12}$$

It is possible to further approximate the operation of a bolometer by relating the heat capacity, cooling constant, and

resistance in terms of the physical dimensions of the bolometer. Also, the voltage E will be limited by the upper tolerable temperature of the bolometer.

These relations are expressed in the following equations.

$$\beta = \gamma lw \tag{13}$$

where l is the length of the strip, w its width, and γ is the heat dissipation per unit area. With such a thin strip the conduction through the lead connections may be neglected.

$$h = lw\left[ac_a + bc\right] \approx lw\,bc \tag{14}$$

a is the thickness of the metal layer, b is the thickness of the membrane support, and c_a and c are their respective specific heats. Because c is about ten times as great as c_a and the thicknesses a and b are comparable, the metallic contribution is neglected. If the bolometer is not operating in vacua, then there will also be a small contribution due to the heating of the gas in the immediate vicinity of the bolometer. This small contribution would be a function of the chopping rate w and would also be related to β, but for simplicity and because it should be small it is neglected. Czerny[2] has expressed some doubt as to the validity of the approximation.

$$R = \rho l/aw \tag{15}$$

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[2] Czerny, Ann. Physik, 8, 65 (1950)

where ρ is the resistivity of the strip.

$$\frac{1}{\beta}\,\frac{E^2}{\rho} = \phi$$

$$E = (\beta \phi R)^{\frac{1}{2}}$$

where ϕ is the highest tolerable temperature of the bolometer strip.

Combining Eqs. (12) through (16)

$$\text{AC sensitivity} = \frac{1}{Y}\,\frac{e}{e_n} = \frac{R}{R+R_s} \propto \left[\frac{\phi}{4k\Theta_A^2 w \Delta f}\left(\frac{\sigma}{b^2 c^2 \omega^2 + \sigma^2}\right)\right]^{\frac{1}{2}}$$

This is as it might be expected. The AC sensitivity is only dependent on R insofar as $\frac{R}{R+R_s}$ is dependent on it. Clearly R_s should be made small compared to R and this is somewhat easier with large R. However, not much increase can be expected in this term. It is desirable to have a high operating temperature β, but this also has a point of diminishing returns when it starts to affect Θ_A.

For high sensitivity a small area is also in order. On the other hand, the incident radiation is proportional to the area in a region of constant flux making the square root of area dependence then come in the numerator. This means that it is best to have a bolometer which is as large but no larger than the image which is to be measured. Even this might not hold precisely under certain circumstances because microphonic noise which is apt to depend on this area might become significant.

The other available variables can be considered as a group. For maximum results ω, b, and c should be small and τ should equal their product. It is not helpful to make ω small since then the rate of gathering information will suffer. b is controlled by the thinnest nitrocellulose membrane tolerable and there is not much that can be done with the specific heat c. τ can be controlled by the gas pressure and the closeness of the strip to the housing.

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